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Comparison of deep foundation solutions for embankments with sensitivity analysis using finite element method

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ABSTRACT: This paper contains a sensitivity analysis of the geotechnical designs of several deep foundation solutions for embankments on soft soils. The selection of the analyzed solutions consists of a basal reinforced piled embankment using rigid inclusion technology, a basal reinforced embankment seated on geosynthetic-encased columns and a basal reinforced embankment on a consolidated foundation with the use of prefabricated vertical drains (PVDs) combined with a geotextile reinforcement. The sensitivity analysis was done for a set of typical design parameters and geometries, with the use of finite element modeling software (Plaxis 2D) and validated with limit equilibrium methods (GEO5, GGU Stability, GGU Consolidation). Examining aspects and limitations of construction time, settlements, overall stability, costs and construction processes, a comparison of deep foundation solutions is carried out based on the outcome of the design analysis.

Keywords: soft soil, piled embankment, PVD, finite element, basal reinforcement

1 INTRODUCTION, PROBLEM STATEMENT

The increasing need for infrastructure development in low-lying areas – like railways, roadway or even airports – often forces engineers to find safe ways of building embankments on soft soils, like soft compressible clays or peaty soils. Complete design of infrastructural embankments on soft foundation strata can challenging to geotechnical engineers, since soft unconsolidated soils cannot sustain external loads without having large deformations and issues related to slope stability, bearing capacity failures and intolerable and/or differential long term settlements should be dealt with care.

The use of geosynthetics during the construction period of embankments on soft soil, particularly for linear embankments (like roadways, railways), has been well established. Usually in case of a single problem, several solutions are applicable. It is a well-known fact that geosynthetics expand the range of soil use in terms of construction speed, cost and constructability, and not the last and in addition, they also reduce the carbon footprint on total project activities. This is why through decades of development, geosynthetics have taken a predominant position in this field and they still offer a broad set of solutions to choose from. Therefore today’s practicing engineers face the challenge, to select the most efficient and cost-effective solutions using just a limited set of local data.

Nowadays, numerous methods for improving stiffness of subsoil exist and civil engineers can offer various strengthening solutions for any specific geotechnical case with distinct soil conditions, loads, and embankment or subsoil geometries. These solutions include, but are not limited to: soil replacement, dynamic soil compaction or impact compaction, soil injection, horizontal geosynthetic reinforcement, gravel piles or vibro-stone columns, prefabricated vertical drains, rigid inclusion, deep soil-mixing, jet grouting, using of lightweight structural materials as embankment like EPS geoboxes.

2 SHORT DESCRIPTION OF THE APPLIED METHODS

In this paper contains a comparison of three different, but commonly used / well-established, solutions / techniques, these are; a basal reinforced piled embankment, a basal reinforced embankment on woven geotextile encased columns and an embankment on soft soil using PVDs and high strength woven horizontally reinforced basal matrass.

2.1 *Prefabricated vertical drains (PVDs)*

From the selection of existing ground improvement schemes as reviewed in this paper, the use of vertical drains is considered as an effective and economical method for improving the shear strength of soft soils and reduce its post-construction settlement (Indrarathna, 2007). By using vertical drains the rate of soil consolidation increases by providing a short horizontal drainage path for water escaping under the excess pore-water pressure / pore water flow. The drainage path is usually shortened from the thickness of a soft soil to half the drain spacing and thereby, reducing the time to complete the consolidation process. (Hansbo, 1981). Consequently, the higher horizontal permeability of the clay is also taken advantage.

These vertical drains have the ability to permit excess pore water in the soil to seep into the drain and transmit the collected pore water along the length of the drain. Since the 1970s, vertical drains have evolved into a completely polymer based prefabricated vertical drain. Nowadays PVDs are applied worldwide to improve foundation/sub soils of runways, highways and railway embankments. Commonly used PVDs consist of a polymeric nonwoven filter jacket surrounding a plastic core. PVDs are installed by a hollow steel mandrel encasing the wick drain material. The mandrel is driven by into the ground by a stitcher attached to an excavator carrier.

A system of vacuum-assisted consolidation via PVD is a practical approach for accelerating consolidation. Such a system eliminates the need for placing high surcharge load, as long as air leaks in the field can be prevented using effective membranes (Indraratna, 2007), (Choa, 1989). Also, there is no risk of short term circular slip failure because of no increment of total stress. Although performance increase of this method equals a conventional PVDs method, it has not been explicitly reviewed in this paper.

2.2 *Geosynthetic-encased columns (GECs)*

Vibro replacement stone columns improve soft soils, like a non-compactible cohesive soil, by the installation of load bearing piles composed/constructed of well compacted, coarse grained fill. The columns densify and reinforce the foundation soil, leading to an increase of global stability, reduction of final settlement and a radical increase of consolidation speed, due to the high discharge capacity of the grain size gravel fill, shortening the drainage path. However, the main disadvantage is the lack of sufficient lateral support of the columns, causing excess final settlements of the designed embankment, see Figure 1.

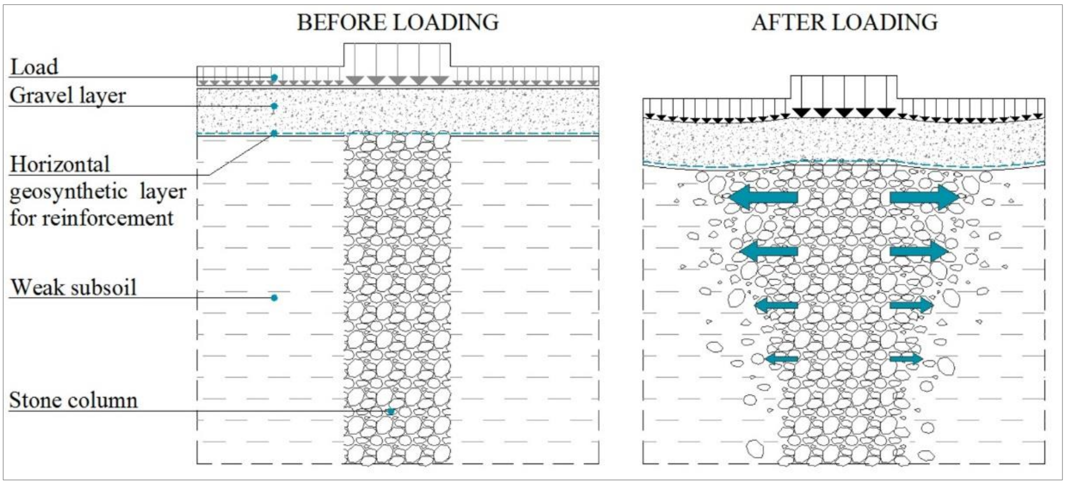

Figure 1: Undesirable increase in pile diameter due to the loading ("bulging" effect)

If the columns are encased in a circular woven geosynthetic fabric or tube, the filter stability between the column fill and the surrounding soil is guaranteed. This geosynthetic tube supports the column fill by resisting the fill's spreading load, transferring it into a circumferential tensile force, thus reducing radial pressure at the adjacent/surrounding soft soil. In this study we will investigate only the gravel columns with geosynthetic encasement, since the finite element programs are not able to take into account the bulging effect.

Stone columns with vibro-replacement method can be a proper technical and economical choice to ensure the stability of embankments on weak ground, when

- the layer of the weak subsoil is relatively thick (or covered with a thin layer with better bearing capacity);
- the critical factors are both the construction time and the final settlements;
- the scope of the area is relatively small (from the engineering point of view);
- close to the construction site gravel or sandy gravel material is available;

2.3 *Rigid inclusion (controlled stiffness columns)*

A commonly used method for improving soft soils is the application of rigid inclusions in soft soils. Rigid inclusions is a ground improvement technique that transfers loads through weak strata to a firm underlying stratum using high modulus, controlled stiffness columns. A bottom-feed mandrel with a top-mounted vibrator is advanced through the weak strata to the underlying firm stratum. Granular bearing soils are densified by displacement. Concrete is then pumped through the mandrel, which opens as it is raised. The mandrel may be raised and lowered several times within the bearing depth to construct an expanded base if required by the design. The mandrel is then extracted while a positive concrete head is maintained. The concrete fills the void created by the mandrel during extraction, and terminates in an upper strong stratum or is subsequently overlain by an engineered relieving platform. The improved performance results from the reinforcement of the compressible strata with the high modulus columns. The technique has been used to increase allowable bearing pressure and decrease settlement for planned structures, embankments and tanks.

2.4 *Summary of the applied methods*

An especially economical way to improve the existing weak foundations is the use of prefabricated vertical drains (PVDs) combined with high strength woven geotextiles and possibly with gradual placement of the embankment fill. This well-established technique allows construction of embankments on weak foundations usually with lower construction cost than using other known ground improvement methods, but often requires considerable time for consolidation and strengthening of the soft ground. Column-supported embankments are constructed over weak subsoils to accelerate consolidation, improve slope and global stability and control the settlements. Columns can be several types depending on the type and geometry of the subsoil, like concrete piles, deep-mixing columns and stone columns. In this paper the following two types will be investigated:

- In an uncased column the lateral support after loading is entirely mobilized by the passive earth pressure of the soft soil which is limited due to the poor physical properties as a result of the undesirable increase in pile diameter which is known as the bulging effect. Using geosynthetic-encased columns (GEC), radial, horizontal column support is guaranteed therefore the final and uneven settlements can be minimalized.
- With rigid inclusion technology (concrete columns) embankments can be built quickly and safely without the need for staged construction therefore the main benefit of using rigid piles is the short time of constructions with good settlement control. However, during the design of the rigid inclusion supported embankments have to take into consideration the negative skin friction and the punching effects, which can represent a non-ductile mechanism of failure.

3 MODEL GEOMETRY AND SOIL PARAMETERS

3.1 *Model geometry*

A potential construction of geosynthetic-reinforced embankment is considered for the study. The embankment is supported via the above-mentioned 3 methods described in Section 2. The embankment geometry is shown in Figure 2 representing an 8 m high embankment of crest width 25.6 m and having side slopes of 1V:1.5H. For a sensitivity analysis various field cases, different soft soil parameters and layer thicknesses were modelled and examined. The applied geometry and soil attributes in the model can be divided into two groups: parameters with constant values and various parameters. Three values for soft soil thickness (6m, 18m and 30m) and 4 soft soil (see in 3.2.2) types were chosen for parametric studies.

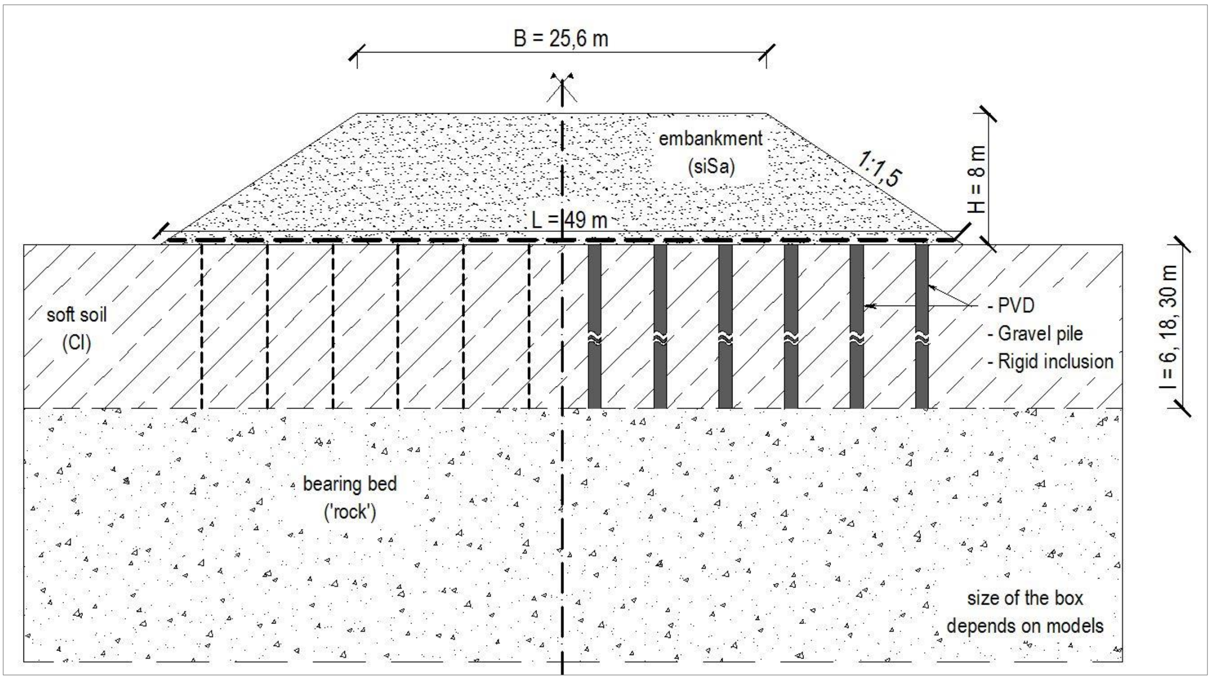

Figure 2: The potential construction of the investigated embankment

3.2 *Material properties and soil models*

The soil parameters are chosen directly for this study based on preliminary experience. The embankment is silty sand as a usual fill material. A sandy gravel reinforced layer with 0.5m thickness is situated between the embankment and the soft soil. This drainage blanket enables the excess pore water to dissipate along the base of the embankments to toes of the side slopes. Limit state design requires the embankment to satisfy two principal criteria: the ultimate limit state (ULS) and the serviceability limit state (SLS). During the selection of the soft soil parameters the objective was to cover a range which allows stability and serviceability problems to occur. The set-up of the calculations is described in Section 4. According to the different analysis types the use of more soil models was necessary. The main principles of the applied models (Mohr-Coulomb and HS small) are summarized in the followings.

3.2.1 *Mohr-Coulomb soil model*

The linear-elastic perfectly-plastic Mohr-Coulomb model involves five input parameters, i.e. Young's modulus (E) and Poisson's ratio (ν) for soil elasticity; friction angle (φ), cohesion (c) and dilatancy angle (ψ) for soil plasticity. The Mohr-Coulomb model represents a 'first-order' approximation of soil behaviour. For each layer one estimates a constant average stiffness. Due to this constant stiffness, computations tend to be relatively fast. The Mohr-Coulomb model is suitable for stability analysis but not appropriate for calculating settlements.

3.2.2 *HS and HS small soil models*

In Hardening Soil model (Plaxis) the relationship is hyperbolic between the vertical strain, ε_1, and the deviatoric stress q in the primary triaxial loading (Bhasi et al. 2015). E_{50}^{ref} modulus is difficult to determine accurately from triaxial tests, so that in general often the Oedometric modulus E_{oed}^{ref} is used. HS small model was introduced in 2007 in Thomas Benz's dissertation.

Table 1: Soil types and soil parameters

Soil classification			High plasticity clay	Moderate plasticity clay		Low plasticity clayey silt	Silty sand	Gravel	Sandy gravel	Stiff silty sand
Soil category			very poor	poor_2	poor_1	moderate	embankment	gravel pile	reinf. layer	bedrock
MC	υ	[-]	0.40	0.40	0.40	0.40	0.30	0.25	0.25	0.30
	γ	[kN/m^3]	19.50	20.00	20.00	20.00	18.50	20.00	20.00	20.00
	γ_{sat}	[kN/m^3]	20.50	21.00	21.00	21.00	19.50	21.00	21.00	20.50
	E_s	[Mpa]	1.50	3.00	3.00	5.00	25.00	75.00	75.00	25.00
	φ_{ref}	[°]	10.00	12.50	14.50	19.00	30.00	40.00	36.00	30.00
	ψ	[°]	0.00	0.00	0.00	0.00	0.00	10.00	6.00	0.00
	c_{ref}	[kPa]	4.00	5.00	6.50	9.00	15.00	1.00	1.00	20.00
	c_U	[kPa]	18.00	24.00	24.00	30.00	-	-	-	-
	k	[m/s]	5.0E-09	5.0E-09	5.0E-09	5.0E-09	5.0E-04	5.0E-03	5.0E-03	5.0E-04
	k	[m/day]	4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E+01	4.3E+02	4.3E+02	4.3E+01
	c_k	[-]	0.40	0.40	0.40	0.40	-	-	-	-
HS	E_{ur}	[Mpa]	4.50	9.00	9.00	15.00	75.00	225.0	225.0	75.0
	m	[-]	0.80	0.80	0.80	0.80	0.50	0.50	0.50	0.50
	e_0	[-]	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50
HSs	G_0	[Mpa]	27.48	49.4	49.4	70.55	-	-	-	-
	$\gamma_{0,7}$	[-]	3.5E-04	2.0E-04	2.0E-04	1.0E-04	-	-	-	-

Using the HS model leads to big strains also in deeper layers – usually the settlements depend on the volume of the 'box' in Plaxis. This issue can be handled with the HS small model as high soil stiffness is considered in small strain levels ($<10^{-5}$). HS small soil model was used in the consolidation calculation in order to estimate settlements as accurately as possible.

The parameters of HS small model are the followings:

- E_{oed}^{ref} - oedometric modulus [kN/m^2]
- E_{50}^{ref} - secant modulus 50% strength [kN/m^2]
- E_{ur}^{ref} - unloading-reloading modulus [kN/m^2]
- m - power law exponent
- G_0 - shear modulus
- $\gamma_{0.7}$ - shear modulus has decayed to 70% of its initial value

4 MODELLING STRATEGY, EXPLANATION OF DESIGNING STEPS

The modelling of the embankment focuses on PVD and gravel pile technologies. These methods are often combined with high strength woven geotextiles to improve the global stability not just during the construction but also considering long-time behaviour. The different technologies can be compared based on the results of stability analysis, consolidation analysis and cost analysis – see the conclusion in Section 6. These are the followings:

- factor of safety from stability analysis,
- settlement from consolidation analysis,
- consolidation time from consolidation analysis.

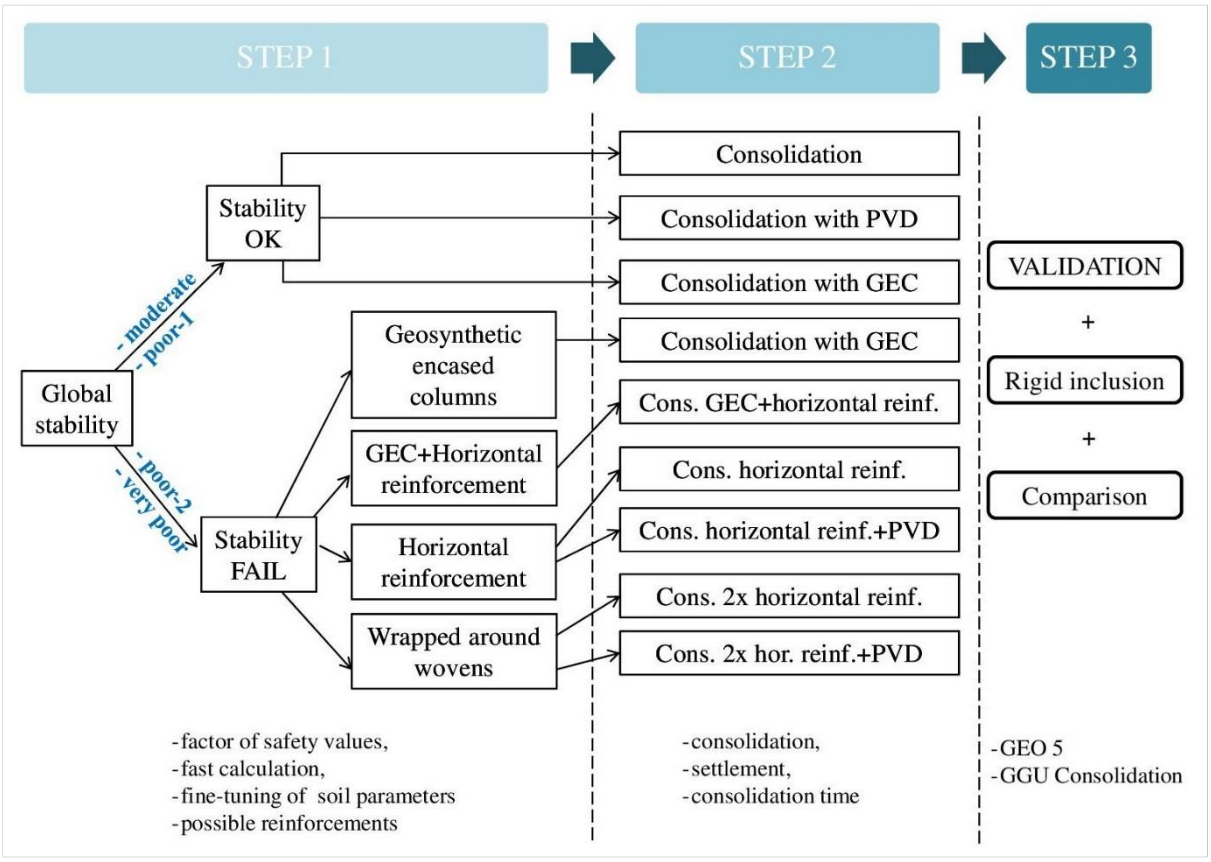

Figure 3: Flow chart of modelling strategy

The stability analysis was carried out in Plaxis 2D and the results were validated based on GEO5. The consolidation calculations were achieved also in Plaxis 2D while the validations were carried out with GGU Consolidation program. Considering these methods individually or combined, the following calculation types were defined for stability analysis:

- soft soil without any reinforcement (using PVD elements has no effect on the final stability of the embankment, hence this type of calculation includes both cases – with or without PVD),
- soft soil with horizontal woven geotextile reinforcement,
- geosynthetic encased columns (GECs),
- geosynthetic encased columns with horizontal woven geotextile reinforcement.

In case of GECs the woven geotextile encasements in Plaxis 2D stability calculation were not installed. However, if slip planes intersect the columns, the resistance of these encasement elements acting to increase stability may be adopted. According to EBGEO (2011), if no special investigation have been carried out, it is recommended not to adopt the elements to the model. Furthermore, different parametric analyses showed that the using and enhancement of the geosynthetic encasement radically (50% or even more) decreases the final settlements. The installed woven PET geotextile as horizontal reinforcement in Plaxis 2D was the same in every geotechnical model. The used reinforcement element has 180 kN/m long term (120 years) design tensile strength, and maximum 10 % elongation at the short term nominal strength.

4.1 *Step 1 (Mohr – Coulomb soil-model)*

These calculation types with 3 different layer thicknesses and 4 different types of soft soil with and without surcharge (20 kPa) mean altogether 96 calculations. As a first step, the stability analysis of these 96 models was carried out with Mohr-Coulomb soil models. The parameters of the soils were finalised during the stability calculations in order to create the following 4 categories:

- *moderate*: meets the requirement for slope stability with 1.25 value but the expected consolidation time is relatively long (1.25 value: according to Eurocode 1997, design approach 3, when the input shear strength parameters (ϕ and c) are characteristic values.)
- *poor_1 and poor_2*: the second category's factor of safety (FS) for slope stability was supposed to be less than 1.25 with long consolidation time. The *poor 1* category's FS was oscillating around the prescribed 1.25, therefore *poor 2* category was created with decreased shear strength parameters.
- *very poor*: the corresponding parameters are far from the values to fulfil the stability criterion (in most cases the calculation stops in Plaxis 2D) and the consolidation time unacceptably long.

4.2 *Step 2 (Hardening Soil small soil-model)*

In Step 1 (Chapter 4.1) all of the geometries with all of the soil and foundation types have been investigated with Mohr – Coulomb soil model to get to know which models are sufficient in the respect of global/slope stability. Obviously those calculations are not enough to make comparable different solution, therefore in Step 2 consolidation calculations have been carried out to analyze the consolidation time, the rate and form of the settlements in the different models. Calculations have been run with the following models:

- *moderate:* Since the safety factors have reached sufficient values in every type of geometry without any basal reinforcement, we have made the consolidation calculations for the unreinforced cases, and also with PVDs and with GECs to speed up the consolidation and also to reduce the settlements.
- *poor_2:* To reach the sufficient safety conditions one layer high strength woven had to be installed to the Plaxis model. Therefore calculations have been carried out without deep

foundation techniques, and with PVDs and also with GEC foundation to reduce the time of the consolidation.
- *very poor*: The minimum safety factors were not achievable with only one layer horizontal reinforcement. The following models have reached the proper safety conditions where we have run the consolidation calculations: GEC foundation with one layer high strength woven layer, two layers wrapped around high strength woven system with and without PVDs, rigid inclusion technology.

The construction of the embankment leads an increase in pore pressure in the soft soil, the effective stress remains low due to the undrained behavior, therefore an intermediate consolidation period have been adopted for a safe construction. During this period the excess pore pressure can dissipate and the soil can have the necessary shear strength to continue the construction process. Based on this condition the embankment construction is divided into two main phases. After the first construction phase (construction of 4m height in 4 days) there is a short period until the consolidation degree reaches the 75% to allow the excess pore pressures to dissipate. After the second construction phase (construction of the rest 4m height in 4 days) there is another construction duration until the degree of saturation reaches 90% and from which the final settlements may be determined. In the design of an embankment it is important to consider not only the final stability, but also the stability during consolidation, for this reason after the second staged construction step the safety factor has been checked in every model.

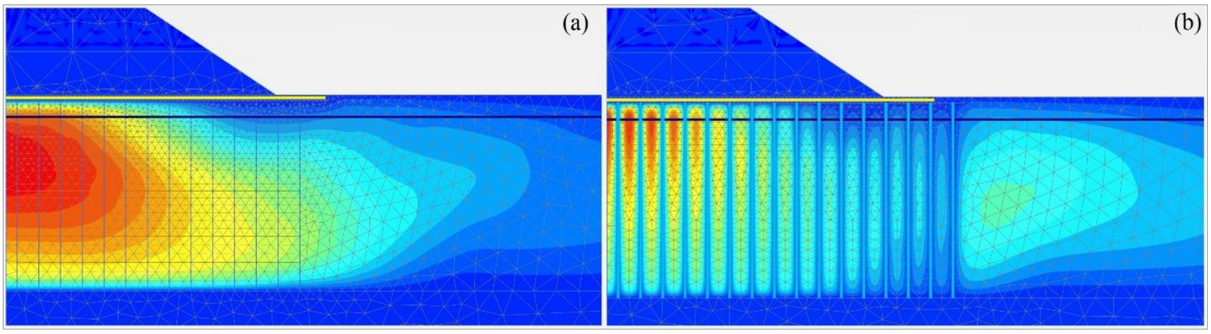

Figure 4: Excess pore water pressure after the second construction phase, poor_2 soil and 18 m soft soil thickness. (a) Without PVDs (313 days), $P_{excess} = 95$ kN/m^2 (b) With PVDs (13 days), $P_{excess} = 61$ kN/m^2

4.3 *Step 3 (Validation)*

GEO5, GGU Stability & Consolidation can offer an attractive and user-friendly alternative to Plaxis 2D approaches for geotechnical problems like embankments on soft soil. At first the stability analysis (Step 1, Mohr – Coulomb soil model) has been checked with the Slope Stability program of GEO5. This program enables analysis of embankment slopes stability with circular or polygonal failure slope surface and automatic optimization, which makes the software applicable and time-saving solution for our validation. Furthermore the program enables geosynthetic reinforcement, surcharge, and installation of gravel piles, hence the stability analysis was feasible for all of the foundation types, soil thicknesses and soil categories.

GGU Consolidate software enables the analysis of classical consolidation processes (analytical and also numerical modelling), similarly to systems with installed vertical drainage can also be investigated. After the modelling the following results can be displayed: tables with the consolidation values at specified times; pore water pressure profile; time-dependent development of degree of consolidation, settlements or pore water pressure; type of load increase. From the results the validation of the Plaxis consolidation analysis (Step 2, Hardening Soil small soil model) was carried out.

5 RESULTS

The results of calculation steps are displayed in this chapter in Table 2, Table 3, and Table 4. The tables include the results of the designing step 1 (stability analysis) and the main outcome of the designing step 2 (consolidation analysis). The numbers are only from the Plaxis 2D finite element software, the validation results can be found after the tables. In the tables the following results are displayed:

- safety factors with and without live load, characteristic soil parameters were used;
- consolidation time in days at 90% degree of consolidation with and without PVDs or with geosynthetic encased columns;
- maximum settlements at the level of the drainage blanket at 90% degree of consolidation with and without PVDs or with geosynthetic encased columns;
- minimum safety factor during the construction with and without PVDs or with geosynthetic encased columns, without live load.

Table 2. Consolidation results, soft soil thickness is 6 meter

Soft soil thickness : **6 meter**										
#	Variables		Safety factors		Consolidation				Min. SF during construction	
	Soft soil type	Solution type	w/out live load	with live load	Cons. time (90%)		Max. settlement		w/out PVD	with PVD
					w/out PVD	with PVD	w/out PVD	with PVD		
1	moderate	Soft soil without rein-forcement	**1.62**	**1.53**	73 days	17 days	22 cm	21 cm	1.43	1.63
2	poor_1		1.38	1.3	-	-	-	-	-	-
3	poor_2		1.22	1.15	-	-	-	-	-	-
4	very poor		1.04	collaps.	-	-	-	-	-	-
5	moderate	Geo-synthetic encased columns	**1.65**	**1.55**	18 days	-	19 cm	-	1.73	-
6	poor_1		1.43	1.34	-	-	-	-	-	-
7	poor_2		1.28	1.2	-	-	-	-	-	-
8	very poor		1.1	1.03	-	-	-	-	-	-
9	moderate	GECs + horizontal rein-forcement	1.83	1.71	-	-	-	-	-	-
10	poor_1		-	-	-	-	-	-	-	-
11	poor_2		**1.62**	**1.47**	20 days	-	28 cm	-	1.58	-
12	very poor		**1.39**	**1.26**	45 days	-	40 cm	-	1.50	-
13	moderate	Soft soil + horizontal rein-forcement	1.83	1.72	-	-	-	-	-	-
14	poor_1		-	-	-	-	-	-	-	-
15	poor_2		**1.52**	**1.39**	127 days	23 days	35 cm	31 cm	1.28	1.42
16	very poor		1.27	1.16	-	-	-	-	-	-
16*	very poor		**1.54**	**1.38**	282 days	41 days	56 cm	50 cm	1.30	1.40
* two layers, wrapped around high strength wovens under the embankment										

The safety factors from designing step 1 are really similar in case of different soft soil thicknesses. For example the safety factor from the 15th calculation (table 2, soft soil thickness is 6m) is 1.39, and 1.38 from the 47th calculation (table 4) when the soft soil thickness is 30 m. The reason of this coincidence is the maximum deepness of the slope circle is around 6 meter, hence the thickness of the soft soil does not have real influence on the safety factors. The only exception is the very poor soil type (16th compare to the 32th and the 48th calculations), where the maximum deepness of the slope circle is around 7-8 meter which causes a decrease in the safety factors. The minimum safety factor during construction with PVDs is much higher (between 10 and 20% increase in the safety factors can be achieved) than without, what means without PVDs in the 31st, 32nd, 47th and 48th calculations the minimum safety factor for the sufficient global stability was not achieved neither with really long consolidation time (more than 7 years in the case of the 48th calculation).

Table 3. Consolidation results, soft soil thickness is 18 meter

Soft soil thickness : **18 meter**										
#	Variables		Safety factors		Consolidation				Min. SF during construction	
	Soft soil type	Solution type	w/out live load	with live load	Cons. time (90%)		Max. settlement		w/out PVD	with PVD
					w/out PVD	with PVD	w/out PVD	with PVD		
17	moderate	Soft soil without rein- forcement	**1.62**	**1.54**	480 days	56 days	43 cm	38 cm	1.43	1.61
18	poor_1		1.38	1.29	-	-	-	-	-	-
19	poor_2		1.22	1.15	-	-	-	-	-	-
20	very poor		1.03	collaps.	-	-	-	-	-	-
21	moderate	Geo- synthetic encased columns	**1.64**	**1.54**	51 days	-	30 cm	-	1.8	-
22	poor_1		1.42	1.33	-	-	-	-	-	-
23	poor_2		1.28	1.19	-	-	-	-	-	-
24	very poor		1.10	1.04	-	-	-	-	-	-
25	moderate	GECs + horizontal rein- forcement	1.82	1.71	-	-	-	-	-	-
26	poor_1		-	-	-	-	-	-	-	-
27	poor_2		**1.61**	**1.47**	66 days	-	46 cm	-	1.82	-
28	very poor		**1.36**	**1.25**	72 days	-	62 cm	-	1.67	-
29	moderate	Soft soil + horizontal rein- forcement	1.83	1.72	-	-	-	-	-	-
30	poor_1		-	-	-	-	-	-	-	-
31	poor_2		**1.51**	**1.38**	768 days	74 days	86 cm	70 cm	1.15	1.38
32	very poor		1.26	1.15	-	-	-	-	-	-
32*	very poor		**1.41**	**1.27**	1357 days	86 days	140 cm	111 cm	1.04	1.22
* two layers, wrapped around high strength wovens under the embankment										

Table 4. Consolidation results, soft soil thickness is 30 meter

Soft soil thickness : **30 meter**										
#	Variables		Safety factors		Consolidation				Min. SF during construction	
	Soft soil type	Solution type	w/out live load	with live load	Cons. time (90%)		Max. settlement		w/out PVD	with PVD
					w/out PVD	with PVD	w/out PVD	with PVD		
33	moderate	Soft soil without rein- forcement	**1.62**	**1.54**	938 days	90 days	49 cm	45 cm	1.43	1.59
34	poor_1		1.38	1.29	-	-	-	-	-	-
35	poor_2		1.22	1.15	-	-	-	-	-	-
36	very poor		1.03	collaps.	-	-	-	-	-	-
37	moderate	Geo- synthetic encased columns	**1.64**	**1.54**	71 days	-	32 cm	-	1.75	-
38	poor_1		1.42	1.33	-	-	-	-	-	-
39	poor_2		1.28	1.19	-	-	-	-	-	-
40	very poor		1.10	1.04	-	-	-	-	-	-
41	moderate	GECs + horizontal rein- forcement	1.82	1.71	-	-	-	-	-	-
42	poor_1		-	-	-	-	-	-	-	-
43	poor_2		**1.61**	**1.47**	64 days	-	49 cm	-	1.83	-
44	very poor		**1.36**	**1.25**	69 days	-	60 cm	-	1.64	-
45	moderate	Soft soil + horizontal rein- forcement	1.83	1.72	-	-	-	-	-	-
46	poor_1		-	-	-	-	-	-	-	-
47	poor_2		**1.51**	**1.38**	1497 days	117 days	98 cm	82 cm	1.16	1.38
48	very poor		1.26	1.15	-	-	-	-	-	-
48*	very poor		**1.41**	**1.27**	2481 days	95 days	163 cm	121 cm	1.04	1.22
* two layers, wrapped around high strength wovens under the embankment										

From tables 2, 3 and 4 it can be also stated that using PVDs reduces the consolidation time e.g. from almost 8 years to only 3 months, and can reduce the maximum settlements with 35%, from 163 cm to 121 cm in the 48th calculation step. The explanation for this reduction can be found in the safety analysis during the construction: due to the low stability of the embankment and the emerging slope circle, the shape of the settlement curve is different than the conventional curve. The maximum settlement is not localized under the center line of the embankment, but there are two symmetrical maximum points ca. 5-10 meter far from the symmetrical axis, see Figure 5.

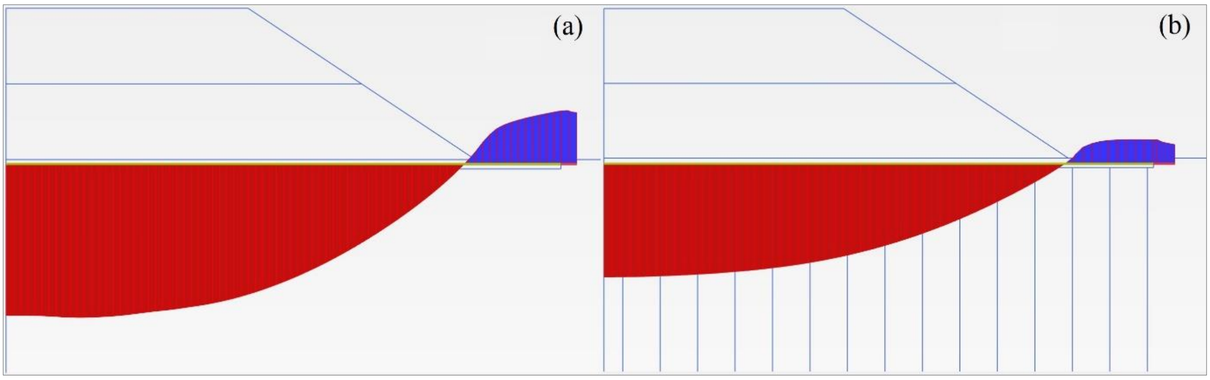

Figure 5: Settlement curves after the second consolidation (90%) phase, very poor soil and 30 m soft soil thickness (a) without PVDs, maximum settlement is 163 cm (b) with PVDs, maximum settlement is 121 cm

Every result (safety factors, settlements, and consolidation times) in this chapter was validated with different geotechnical programs according to section 4.3. After the comparison between Plaxis 2D safety factors and GEO5 verification it can be stated that the difference ~~is~~ varies between 1 and 6% regarding the global stability. Most of the results of GGU Stability were really similar to results of Plaxis 2D, but with increasing soft soil thickness the differences increase as well. Most likely the reason for this is the use of hardening soil model in Plaxis 2D, since the GGU Consolidation uses analytical method which leads to more conservative results in settlement and consolidation time. It means that with GGU Consolidation the difference is more significant between the cases installing PVDs or not.

Regarding the rigid inclusion technique only three calculations were carried out (16th, 32nd and 48th calculations) by the reason of the complexity of its Plaxis model. In all of the cases the factor of safety values were sufficient with similar pile-distance as it was in case of the gravel piles, but consolidation calculations were not realized.

6 COST ESTIMATION & CONCLUSION

Whilst costing of the finished schemes varies significantly based upon site location, location and availability of concrete, steel and gravel there are sufficient consistencies to enable us to compare approximate finished construction costs for the different construction methods. In order to simplify the cost estimation identical or sufficiently similar items such as road construction, granular working platform for foundation rigs and the construction of the bulk embankment were not included in the costing whilst the duration of the foundation activities and embankment construction was maintained at approximately the same level for each individual depth of founding strata so that the site ancillary running costs remained constant for all 4 solutions.

Within the PVD costing the costs included were the rig mobilization and demobilization, PVD supply and installation, supply and placement of the granular layer within the basal mattress and supply and installation of the basal reinforcement, the construction period was adjusted to allow for the consolidation period and the additional fill supply, placement and compaction required to make up the full embankment height was included. Estimated construction costs varied from around €900 per linear meter of embankment for the 6m founding depth to €1,340 per linear meter at 30m depth.

The GEC solution was costed to allow for the rig mobilization and demobilization, supply of sleeve and gravel infill and installation, supply and placement of the granular layer within the basal mattress and supply and installation of the basal reinforcement. Estimated costs varied from around €3,000 per linear meter of embankment for the 6m founding depth to €12,700 per linear meter at 30m depth.

The piled solution costing allowed for the rig mobilization and demobilization, boring and casing, steel supply and fix, cage placement including service cranes, concrete supply and placement including, supply and placement of the granular layer within the basal mattress and supply and installation of the basal reinforcement. Estimated costs varied from around €4,000 per linear meter of embankment for the 6m founding depth to €16,500 per linear meter at 30m depth.

The conclusions to be drawn from the costing are clear in that the importation and placement of bulky materials significantly increases both the cost and the carbon footprint of the project with a GEC solution offering around 25% savings over more conventional concrete piled solutions with that saving potentially increasing if a local source of rounded gravel or sand is available for use within the columns whilst the PVD solution offered savings of 80 to 90% of the cost of the piled solution due to almost complete elimination of bulky material import and the more rapid installation rate of PVDs when compared with either piling or GECs even when the consolidation period is taken into account.

As a conclusion it can be stated that more different methods are available to increase the global stability and reduce the consolidation time and settlements of an embankment. The most appropriate technique can be chosen only with the local circumstances taken into consideration. Based on the results of the Tables and cost calculation a global overview is offered.

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